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**TITLE: DYNAMIC ANALYSIS OF SHOULDER-FIRED WEAPONS**

PHILIP D. BENZKOFER

U.S. Army Armament Research, Development & Engineering Center
Light Armament Division
Simulation & Evaluation Branch
Picatinny Arsenal, NJ 07806-5000

ABSTRACT:

A recoil analysis to assess several recoil mitigating technologies applied to shoulder-fired weapons such as a grenade launcher or shotgun has been conducted. Parameters such as weapon weight, recoil impulse, recoil velocity and recoil energy were identified as critical. A range of values were selected for evaluation. In order to monitor and assess the dynamics occurring during its cyclic motion, a mathematical model for a 12 Gauge weapon has been developed. The model defines each major component and the relative connectivity between them is defined in terms of kinematic joints. A Lagrangian methodology is utilized to formulate the rigid body dynamic equations of motion. Three commercial recoil reducing devices were evaluated in the model to determine their specific effect on recoil motion, both on the weapon and on the soldier firing the weapon. A full test program was conducted at the Armaments Research Laboratory (ARL) on a modified 12 Gauge shotgun to measure recoil control for each of the recoil devices. An additional model was formulated for this fixture. Comparisons between model and experimental test results were made. Further tests and evaluation include combinations of recoil devices. Documentation of sample model output is included.

94-14468

**BIOGRAPHY:**

PRESENT ASSIGNMENT: Armament/Weapon/Mechanisms Analysis, US Army Armament Research and Development Center, 1977 to present.

PAST EXPERIENCE: Math Analysis, GEN T.J. Rodman Laboratory, Rock Island Arsenal, IL, 1966 to 1977.

DEGREES HELD: B.S., Mathematics, Iowa State University, 1965, M.S., Mechanical Engineering, University of Iowa, 1980.

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DYNAMIC ANALYSIS OF SHOULDER-FIRED WEAPONS

PHILIP D. BENZKOFER

U.S. Army Armament Research, Development and Engineering Center
Close Combat Armaments Center
Picatinny Arsenal, NJ 07806-5000

INTRODUCTION

The primary objective of the Parametric Recoil Analysis program was to create computer models that are capable of quantifying the effectiveness of recoil mitigating devices in shoulder fired grenade launchers/weapons with known weapon weights and cartridge characteristics. Early models were concentrated on the M203 system as a baseline. Followon analyses were concentrated on modeling a 12 Gauge weapon installed in a firing fixture designed and fabricated by the Armaments Research Laboratory's Weapons Branch at Aberdeen Proving Grounds. This decision was based upon the fact that physical data obtained from firing from the test fixture would provide the basis for model comparison. The ARL fixture was designed to simulate the motion of a shooter's shoulder, represented by a sliding mass, when firing a weapon. The capability to incorporate shock absorbers and recoil pads was designed into the fixture. By comparing the model results to the actual test fixture results, a good correlation could be obtained. By obtaining this correlation, the necessity to test future shock absorber designs is substantially reduced or eliminated.

The ultimate goal was to produce a model for use in determining the characteristics of an "ideal damper" based upon known ammunition parameters and weapon configuration. In this way, damping parameters can be input to the model until the best recoil mitigating results are obtained. The damper can then be designed around those damping characteristics. This provides the background for the subject paper. A detailed description of the system and the analysis performed along with the results follows below.

WEAPON SYSTEM MODELING

In order to address the analysis of the weapon, a brief description of the weapon is relevant. Initial analyses were based upon the 40mm M203 grenade launcher system. However, based upon a test program conducted at ARL using a 12 Ga Remington, this system was selected for a modeling effort. A test fixture for the test firing program was designed and built (see figures 1 and 2) at the ARL facility, where the test firings were conducted. A later fixture was developed which substantially reduced the weight of the sliding mass,

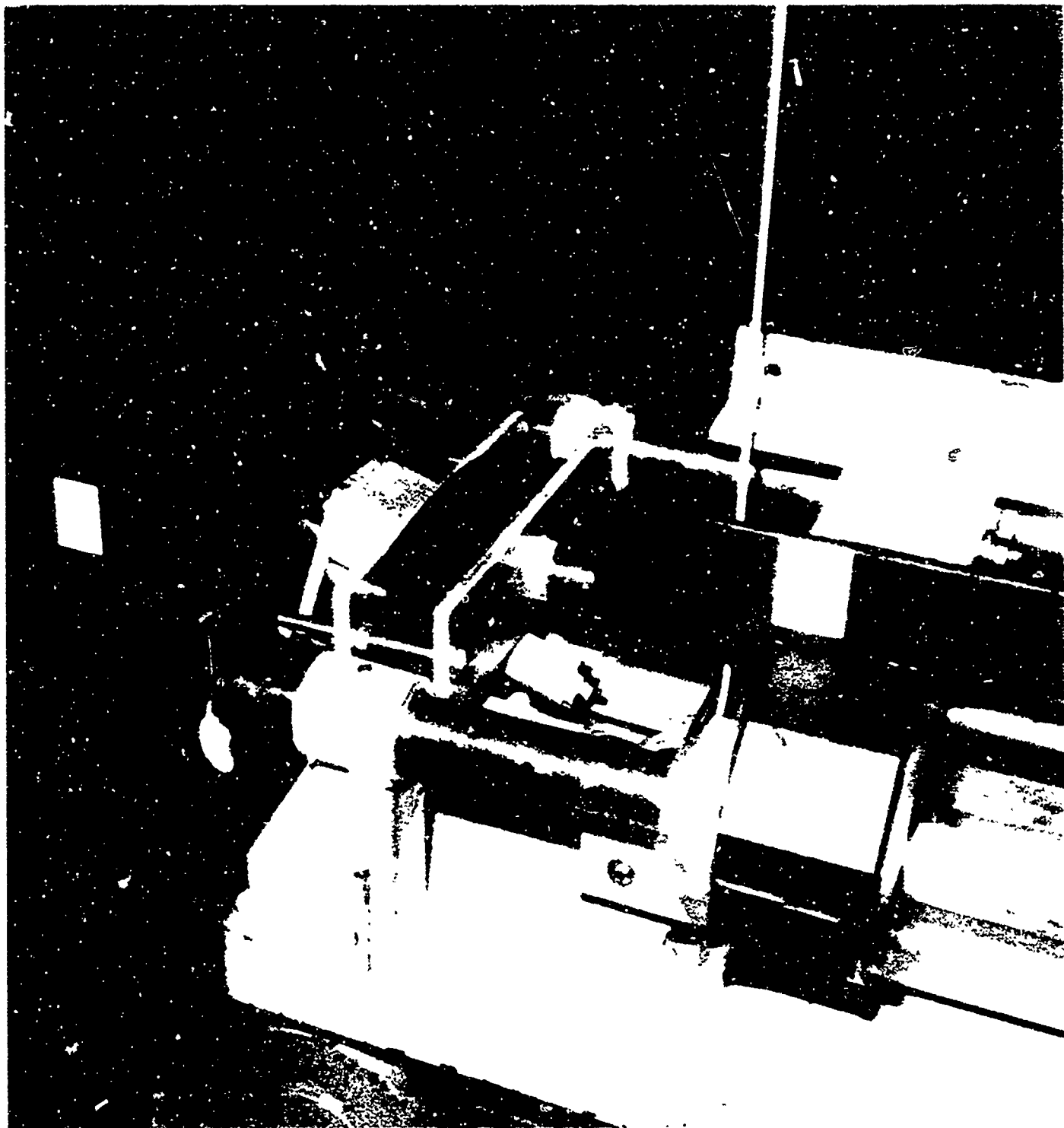


Figure 1. ARL test fixture and weapon

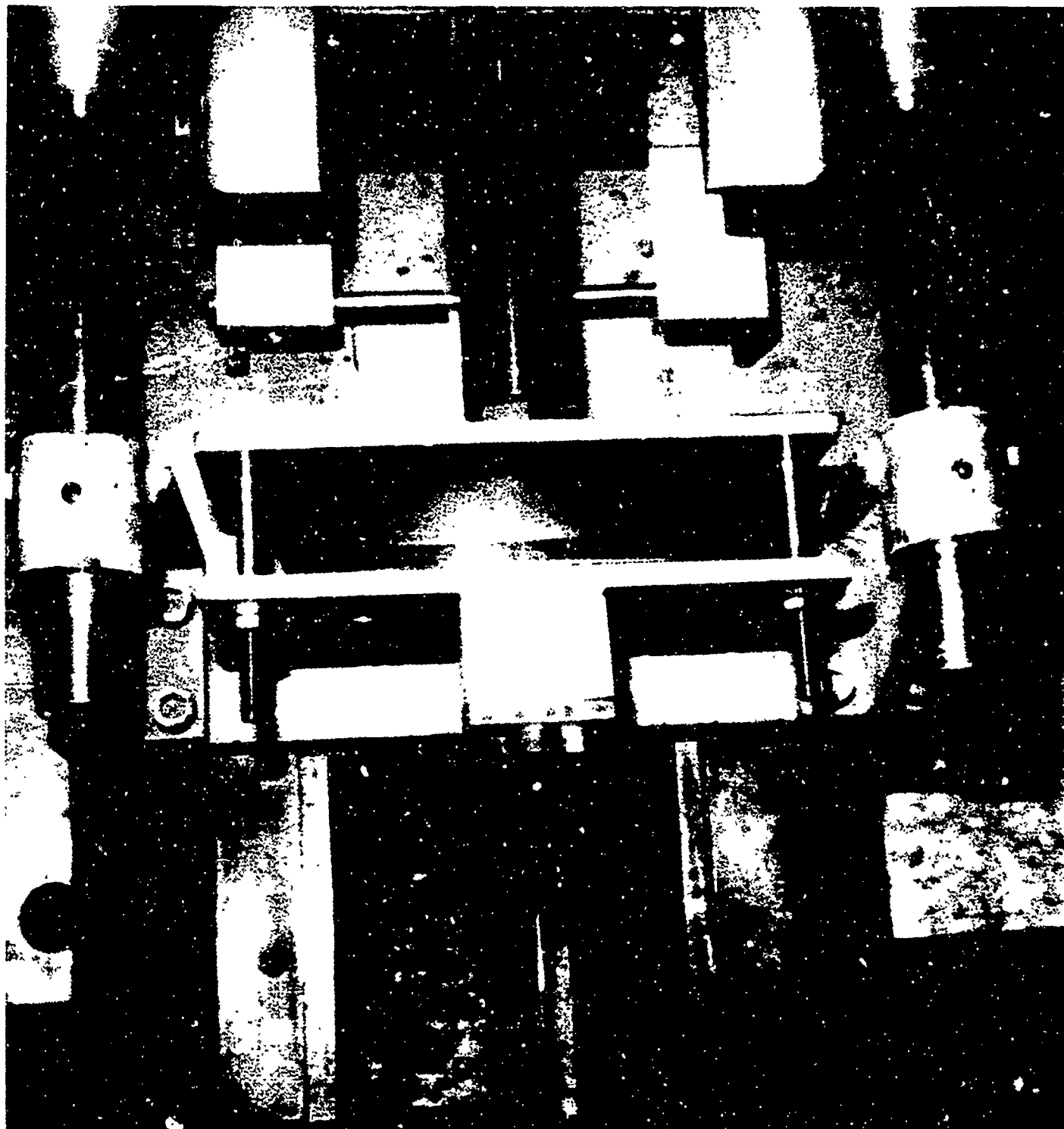


Figure 2. ARL test fixture and weapon

which represents the shoulder mass. This reduction in mass was based upon initial testing results, indicating the first translating mass shown in figures 1 and 2 did not replicate actual motion. The fixture did, however, allow for the development of a generic computer model. The 12 Ga weapon was modified by cutting the stock and constructing a translating fixture which would allow for insertion of the recoil devices and pads. Three specific rounds of ammunition - a target load, a rifled slug load and a heavy magnum load, were utilized in testing, consequently their pressure-time curves were used in the model as system drivers. A typical curve is shown for the magnum round in figure 3. A schematic drawing representing the ARL fixture/weapon system is shown in figure 4. This schematic actually represents the later test fixture described above which was developed to change the mass of the translating mass. Mass one with coordinates x_1, y_1 represents the Inertial Reference Frame from which all global measurements are made. Mass two with coordinates x_2, y_2 represents the mass center of the shoulder, mass three with coordinates x_3, y_3 represents the mass center of the rifle and finally mass four with coordinates x_4, y_4 represents the mass center of the projectile. The associated coordinates are shown on the figure. Connectivity is indicated by spring and damper pairs k_1, c_1 and k_2, c_2 between masses one and two and k_3, c_3 and k_4, c_4 between masses two and three. The spring and damper pairs between masses one and two represent two springs with $k_1 = k_2 = 149$ lbs/inch and $c_1 = c_2 = 0$. The operating height of these two springs is 4.4 inches, which is also the free length. The spring and damper pair represented by k_3, c_3 is a recoil dissipating device such as a shock absorber where k_3 is a constant value and c_3 is variable with velocity. The spring and damper pair represented by k_4, c_4 is a secondary dissipative device such as a pad where measured values are utilized for k_4 and c_4 . The variable pressure time curve for the ammunition is applied to the projectile in the forward direction and conversely applied to the rifle in the rearward direction. The dynamic equations of motion are code generated [1] and are in the Lagrangian form given by

$$\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} - Q_i + \frac{\partial \Phi}{\partial q_i} \lambda = 0, \quad i = 1, \dots, N \quad (1)$$

where

T is the kinetic energy
 q_i are the generalized coordinates
 Q_i are the generalized external forces acting on the system
 λ is the set of Lagrange Multipliers associated with the constraints imposed on the system

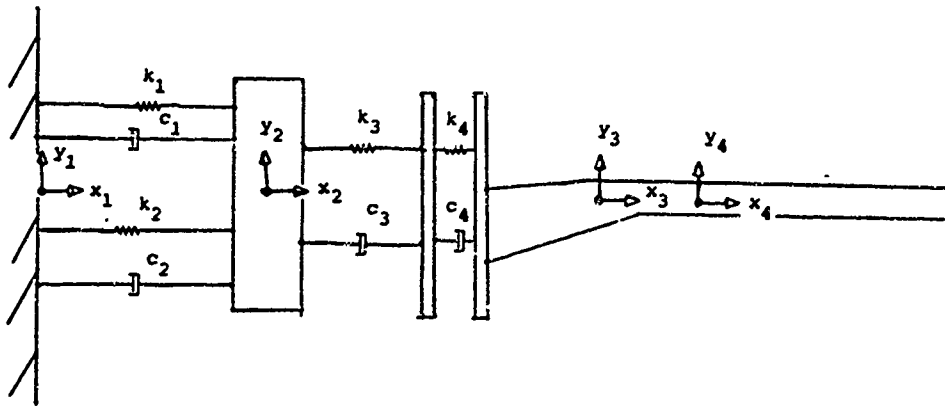


Figure 3. Schematic model of weapon

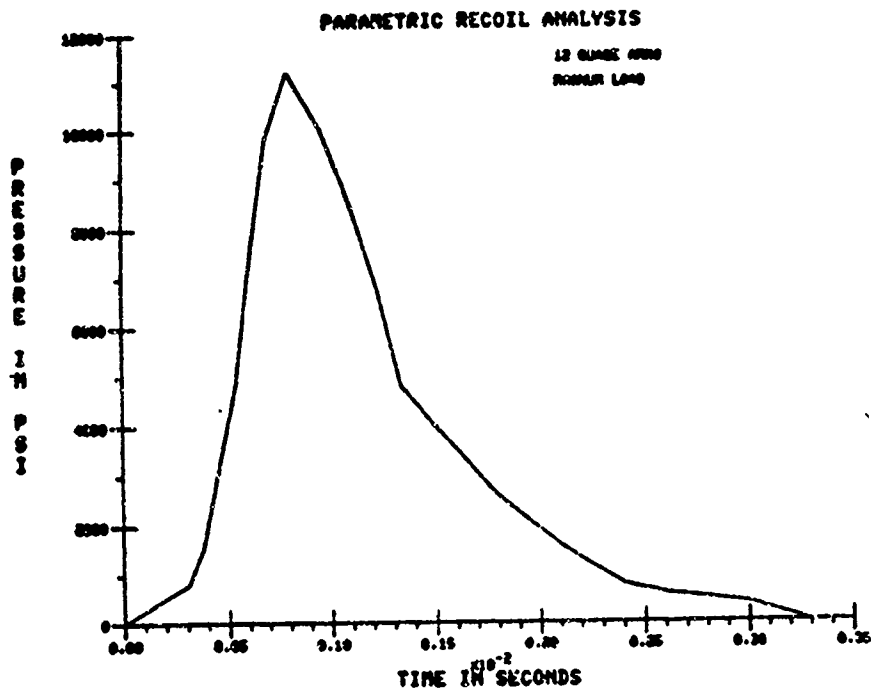


Figure 4. Pressure-Time curve for 12 Ga ammo

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The equations of constraint are of the form

$$\phi(q,t) = 0 \quad (2)$$

These equations represent the mathematical description of constraining motion. The model, then, can be exercised to obtain the dynamic motion for given parameter changes such as spring damper rates. This analysis provides the basis for any future design and/or redesign efforts. The author has significant experience in application of dynamics code to weapon and armament system analysis in [3] through [11].

ANALYSIS

Mass two, the shoulder, on the ARL fixture, (see figure 4) weighed 32 pounds. This weight was utilized based upon a previous man-weapon analysis [2]. There were no springs between masses one and two, so effectively $k_1 = c_1 = k_2 = c_2 = 0$, as shown in figure 4. Two of the most promising shock absorbers based upon initial testing and analysis were selected for inclusion in this paper. Curves depicting velocity versus damping coefficients for these two shocks are shown in figures 5 and 6, and provide the force effects of the shock absorbers. These data were furnished by the manufacturers.

The first series of output given in figures 7, 8 and 9 depict displacement, velocity and acceleration versus time, respectively, for the translating mass, or shoulder (for the early BRL test fixture model shown in figures 1 and 2). In each of the figures the motion for the cases of no shock, an Ace and a Taylor shock absorber is shown. The ammunition round is the magnum round with its P-T curve shown in figure 4. The significant difference in absorber effect is best shown in figure 9 for accelerations, where the magnitude is substantially greater for the case with no shock absorber. Similarly the displacement, velocity and acceleration versus time for the rifle is shown in figures 10, 11 and 12, respectively. The velocities in figure 11 are significantly higher for cases with the shock absorbers as compared with the translating mass in the previous figures, as is also the case in figure 12 for accelerations of the rifle. For the case of the ARL test fixture with the lighter translating mass, specifically 11-12 pounds, it is shown schematically in figure 4. The early ARL test fixture weighed 32 pounds and did not have the two large springs represented by k_1 , k_2 , c_1 and c_2 in figure 4. The displacement, velocity and acceleration versus time for the translating mass, or shoulder, are shown in figures 13, 14 and 15, respectively. The significant difference in shock absorber effect is best shown in figure 15 for acceleration, with the magnitude being substantially greater for the case of no shock absorber. The displacement, velocity and acceleration versus time for the rifle are shown in figures 16, 17 and 18, respectively. Some increase in velocities over that for the translating mass, or shoulder, is noted for the cases with shock

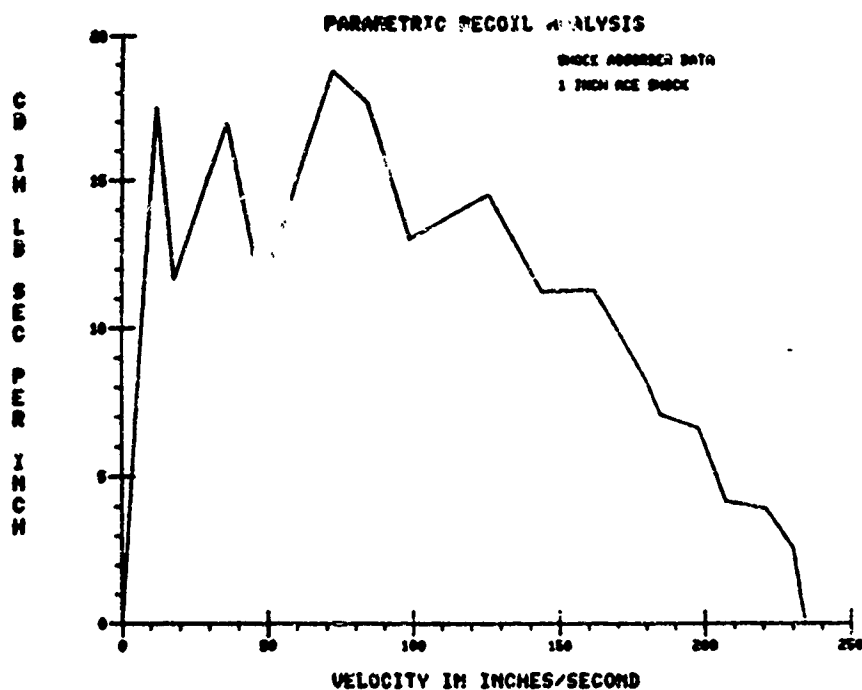


Figure 5. Damping coefficient versus velocity for Ace shock

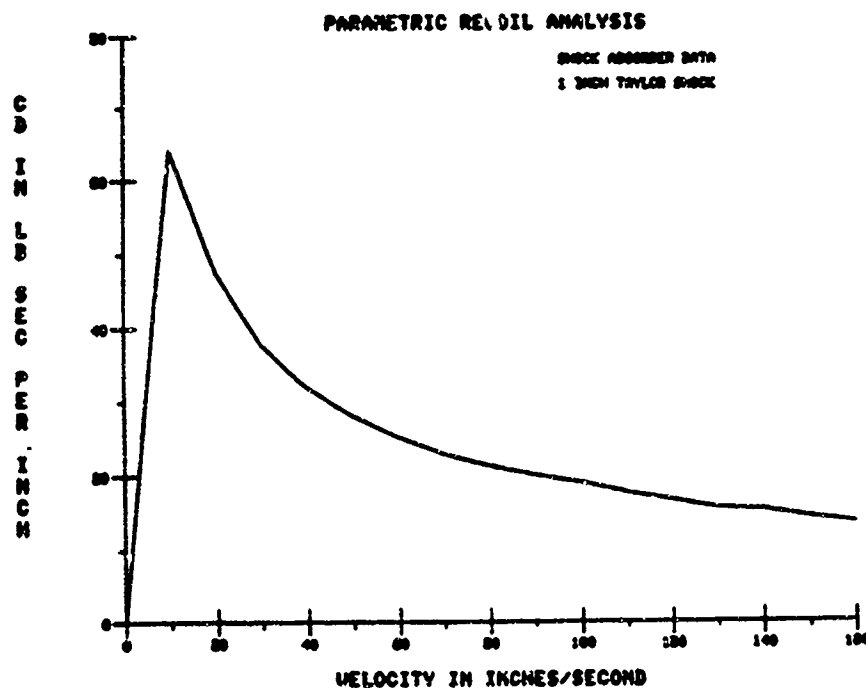


Figure 6. Damping coefficient versus velocity for Taylor shock

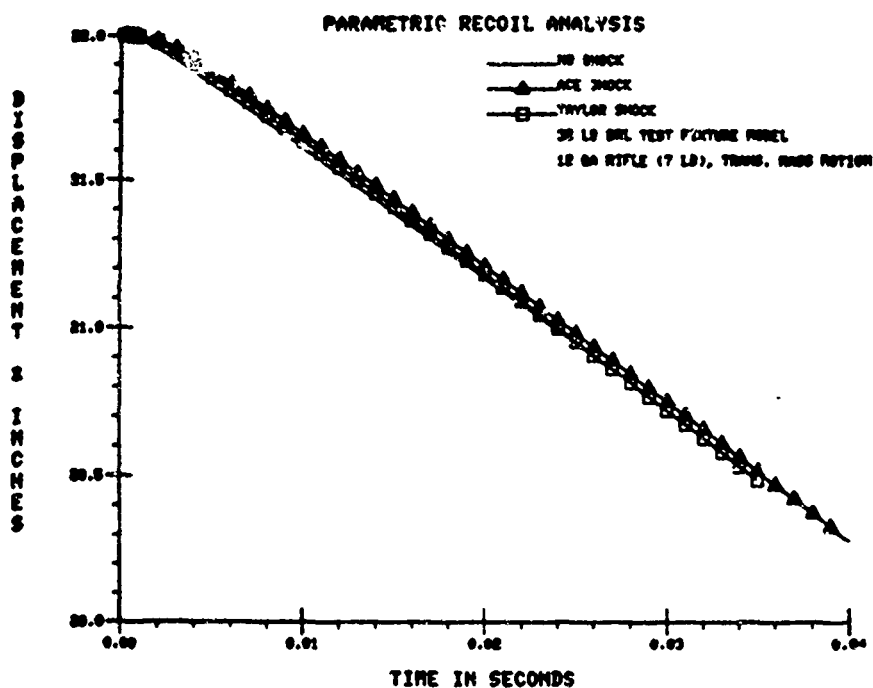


Figure 7. Displacement versus time for shoulder mass

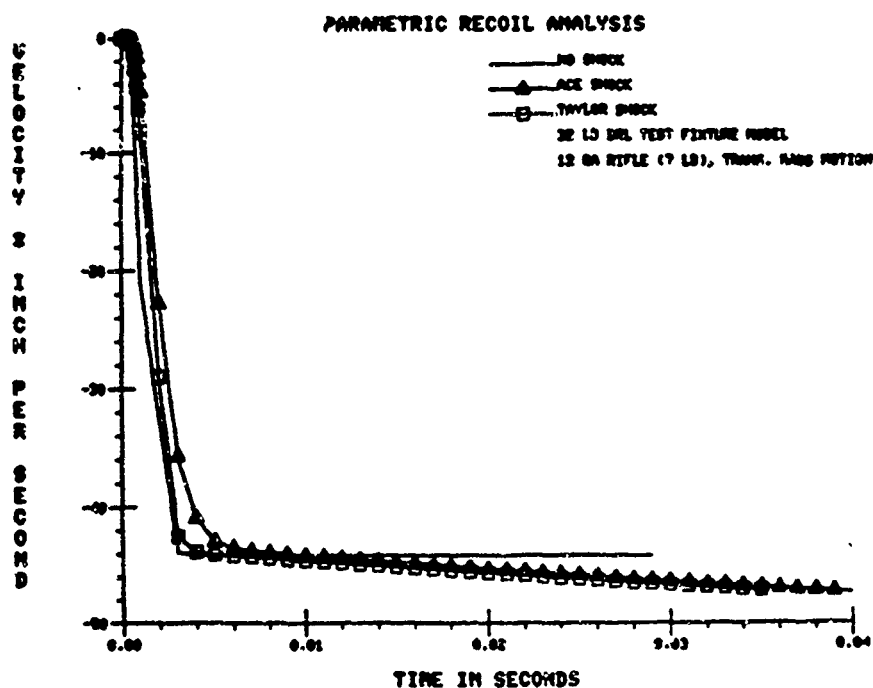


Figure 8. Velocity versus time for shoulder mass

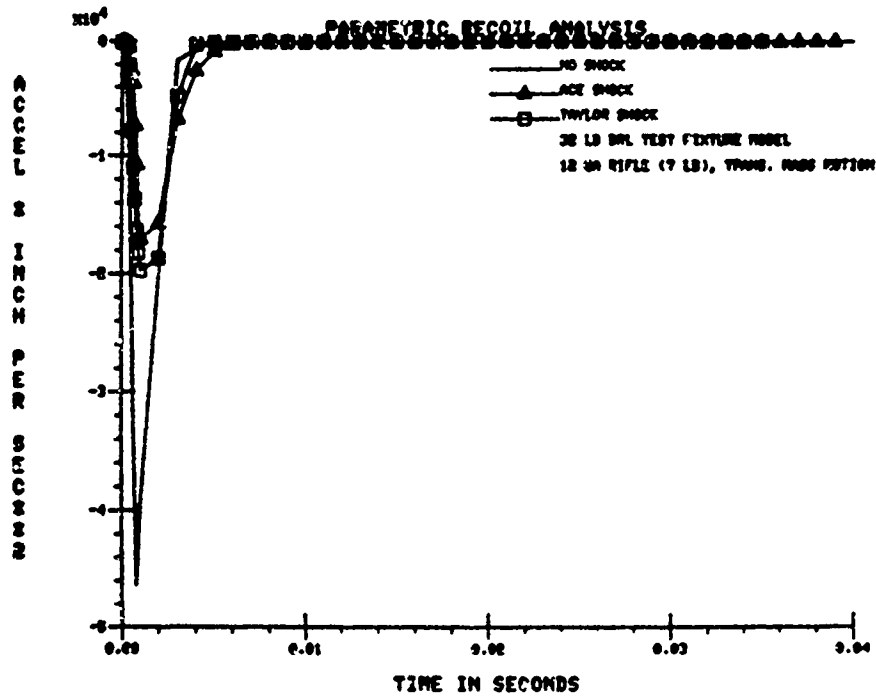


Figure 9. Acceleration versus time for shoulder mass

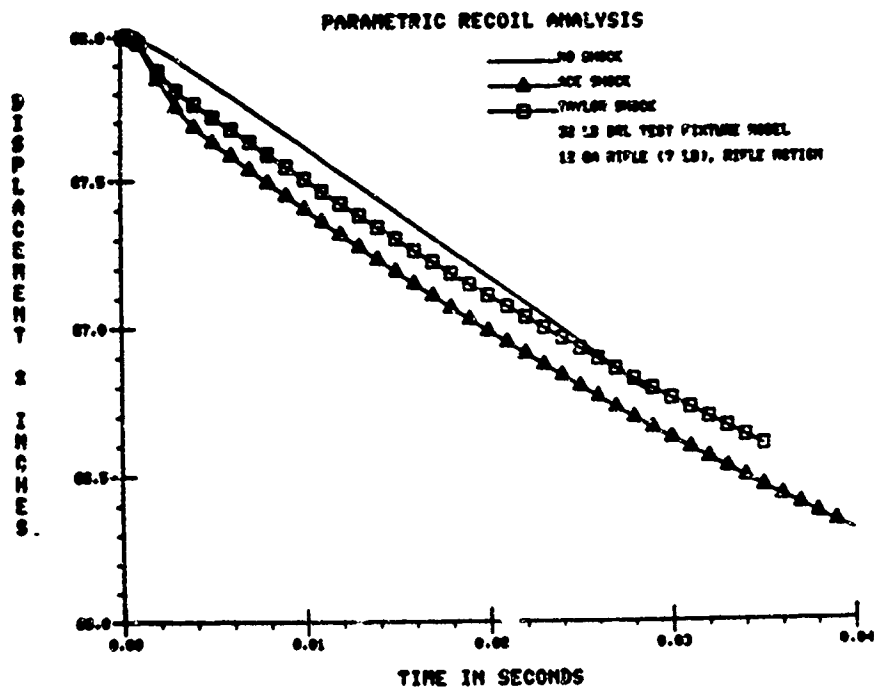


Figure 10. Displacement versus time for rifle

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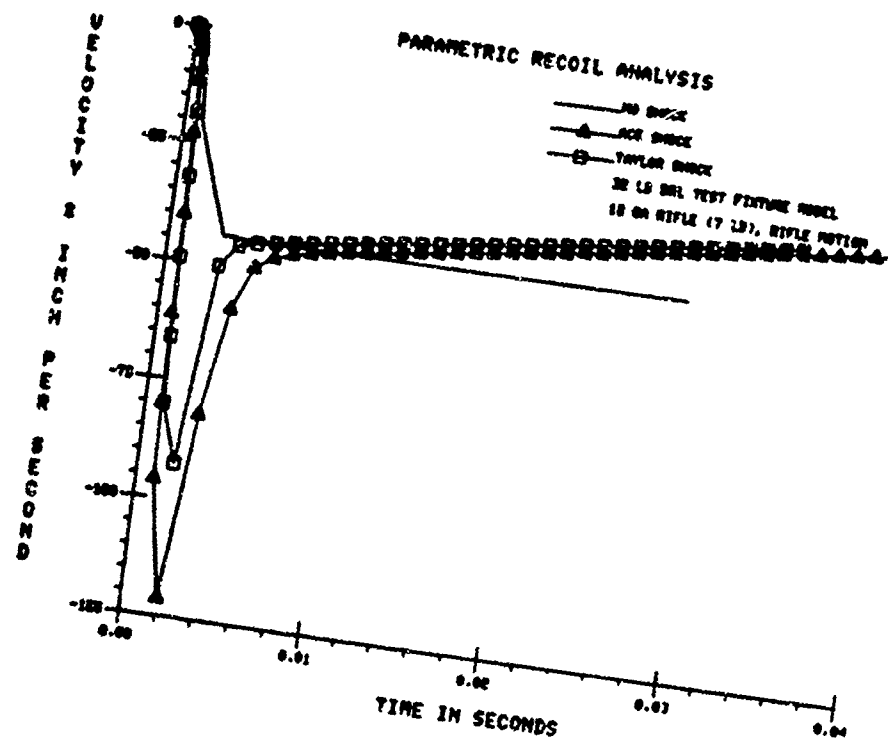


Figure 11. Velocity versus time for rifle

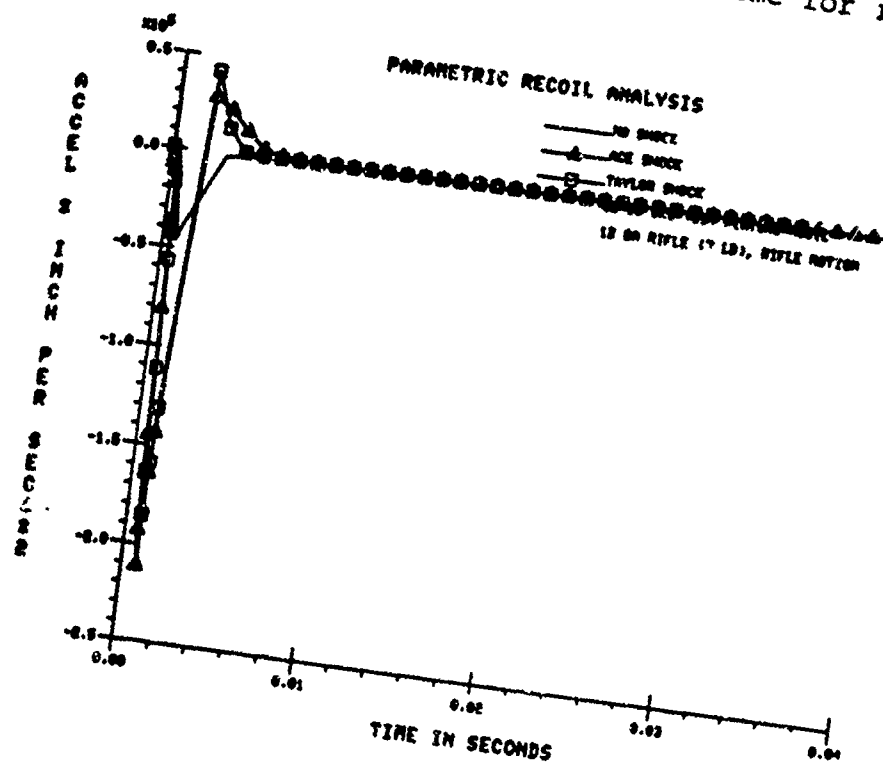


Figure 12. Acceleration versus time for rifle

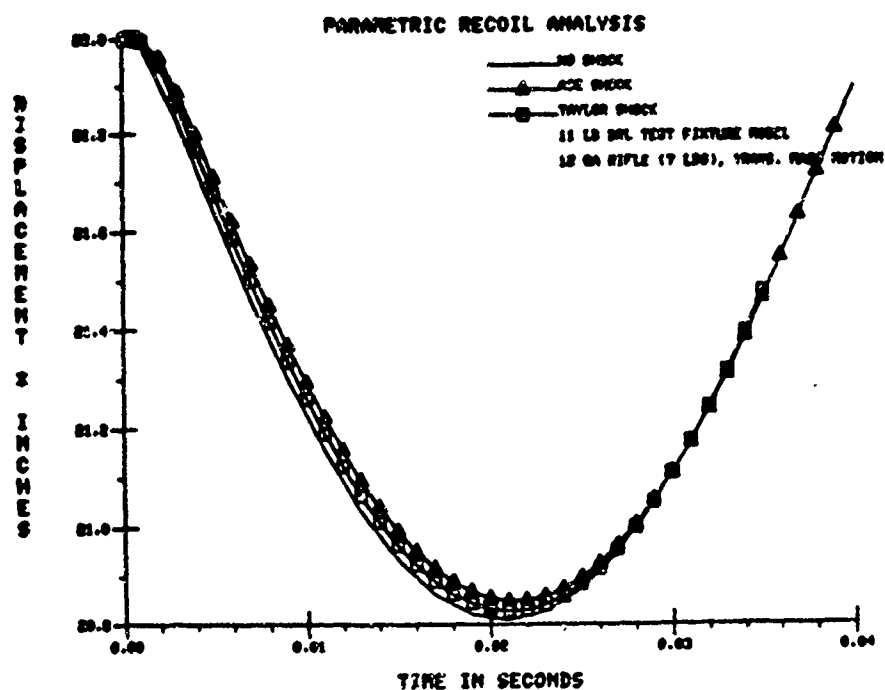


Figure 13. Displacement versus time for shoulder mass

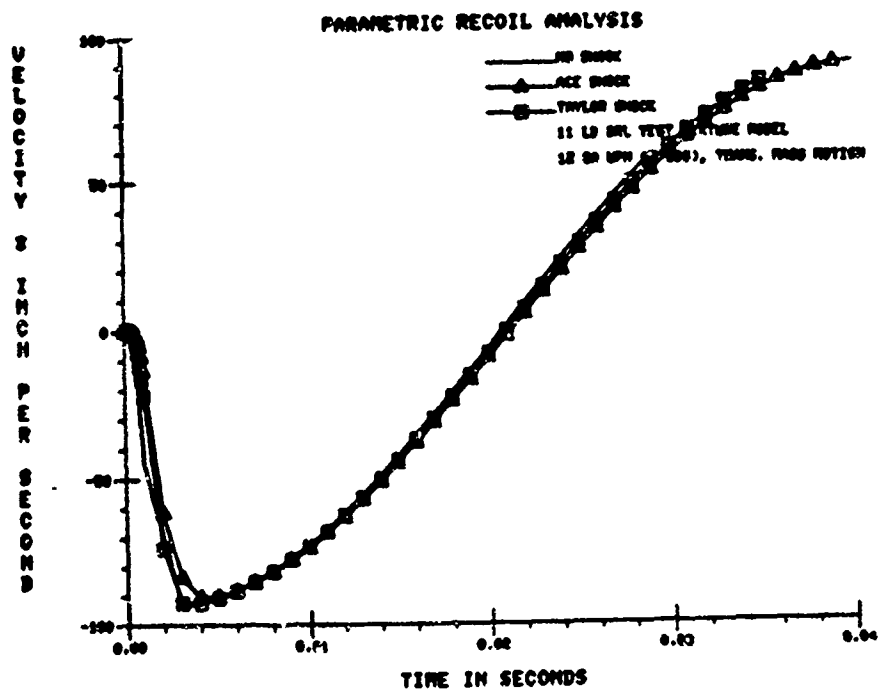


Figure 14. Velocity versus time for shoulder mass

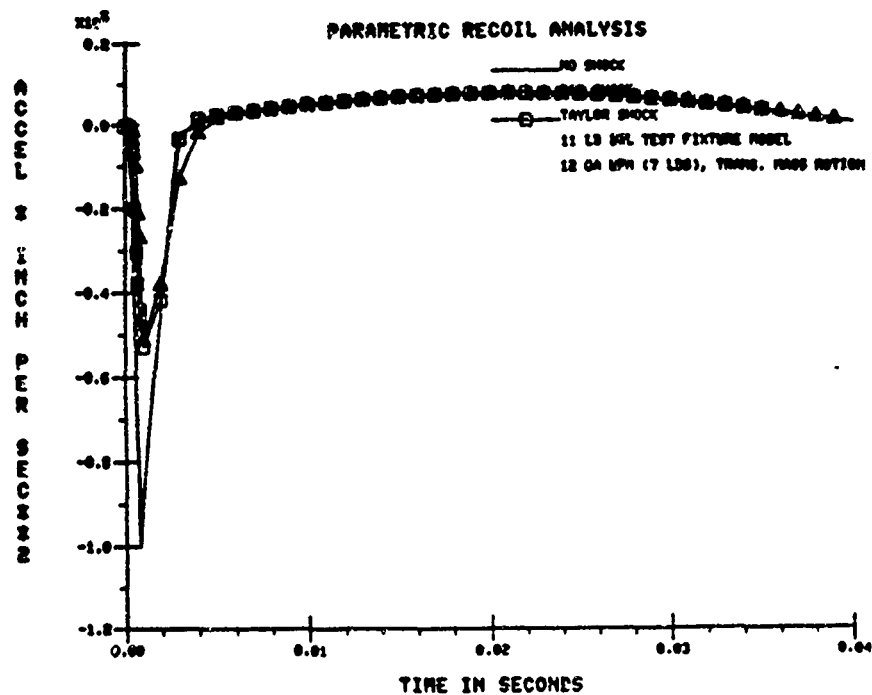


Figure 15. Acceleration versus time for shoulder mass

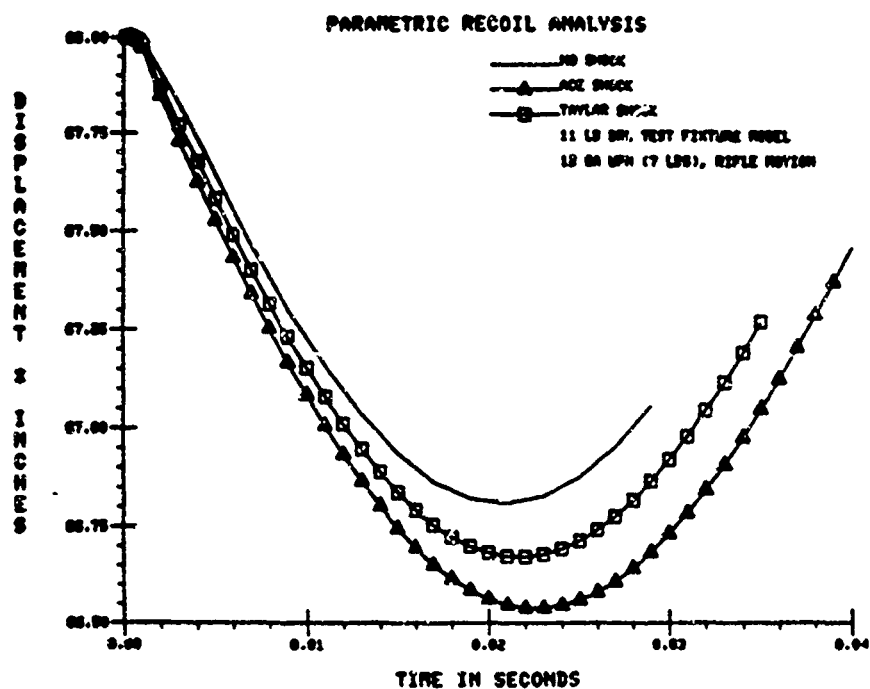


Figure 16. Displacement versus time for rifle

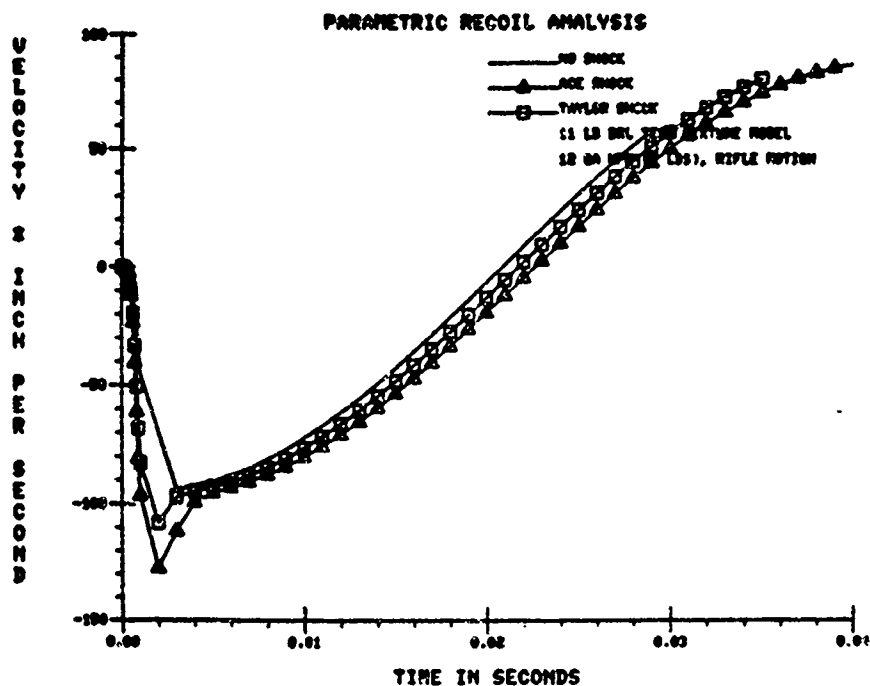


Figure 17. Velocity versus time for rifle

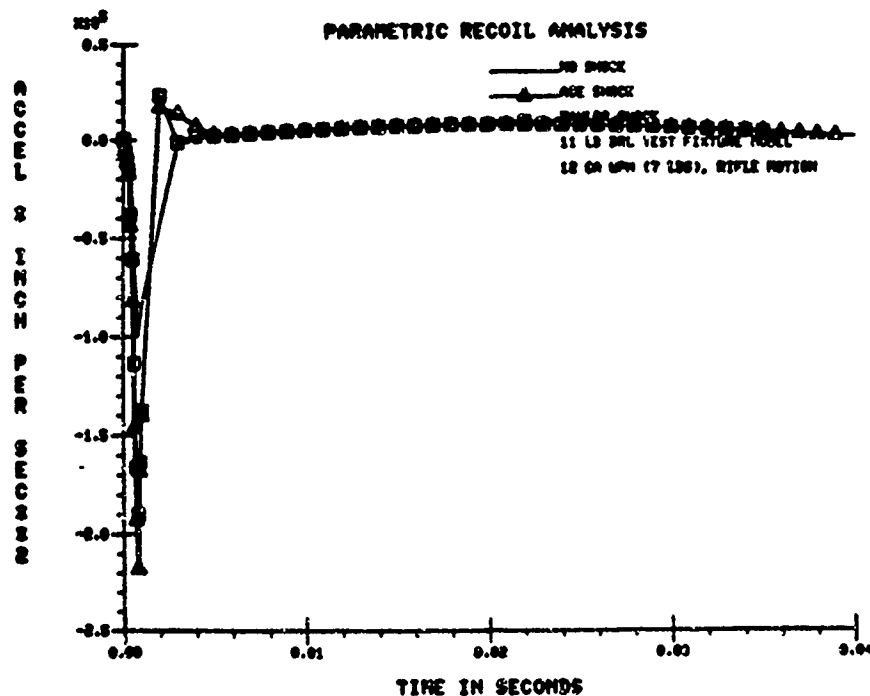


Figure 18. Acceleration versus time for rifle

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absorbers. Substantial increases in accelerations for the shock absorber cases over that for the shoulder are also depicted in figure 18.

In order to assess the effect of varying the damping rates associated with the shock absorbers, a series of analyses were made. The Ace shock was arbitrarily selected to evaluate differences in performance. The case for a damping rate equal to that used in the analyses to date was used as a reference, and two additional rates were selected. These are specifically fifty percent and thirty percent of the damping rate used to date. The displacement, velocity and acceleration versus time for the translating mass, or shoulder, for the three cases are shown in figures 19, 20 and 21, respectively. Interestingly, a decrease in damping rate decreases peak velocities and accelerations. Conversely, looking at the displacement, velocity and accelerations versus time for the rifle, respectively, shown in figures 22, 23 and 24, a decrease in damping rate increases peak velocities and accelerations. A change in damping rate, then, has significant impact on the motion.

Several comparisons between simulation results and experimental data from ARL testing are shown in figures 25, 26, 27 and 28. Figure 25 shows displacements versus time for the magnum round with no shock absorber for ARL test data versus simulation results. Similarly, displacements for the case when a shock absorber is used is shown in figure 26. Figure 27 shows velocities for a magnum round and finally figure 28 shows accelerations for the case of no shock absorber. In general, good comparison is made in terms of displacements and velocities. Acceleration tracks relatively good up to peak and even after peak except a shift does occur.

CONCLUSIONS AND RECOMMENDATIONS

Some inaccuracies are apparent when observing motion results as simulation values do not fully coincide with test data. Several significant factors may well have affected the results as provided in the figures above. One, the pressure-time curve used for the 11 pound shoulder mass model is based on Remington's Magnum round, and the round used at ARL for the 11 pound system was the Duplex round. Even though the impulse measured was similar, there very well could be a shift in the actual curve's shape. The second important factor is that the damping curves used in the simulation are based on manufacturer-furnished data, and some error may exist in this data. The last factor is the accuracy of the model itself. Although a good check has been made of the math model and the input to the code, and the fact that the code itself is felt to be a verified one, further investigation is warranted. Good match with displacement and velocity is shown, and in general peak accelerations are matched. However, some shift in curve shape and magnitude values are evidenced. Further Remington data has been requested and further interface with the shock absorber manufacturers will be pursued. A good model of the ARL fixture has been developed and will provide the basis for further analysis and investigation.

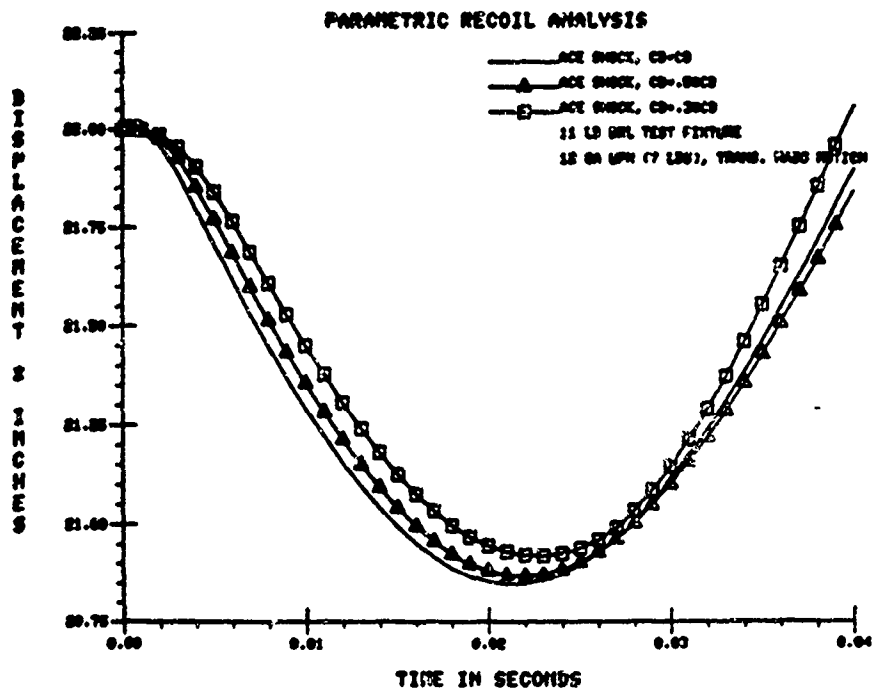


Figure 19. Displacement versus time for shoulder mass

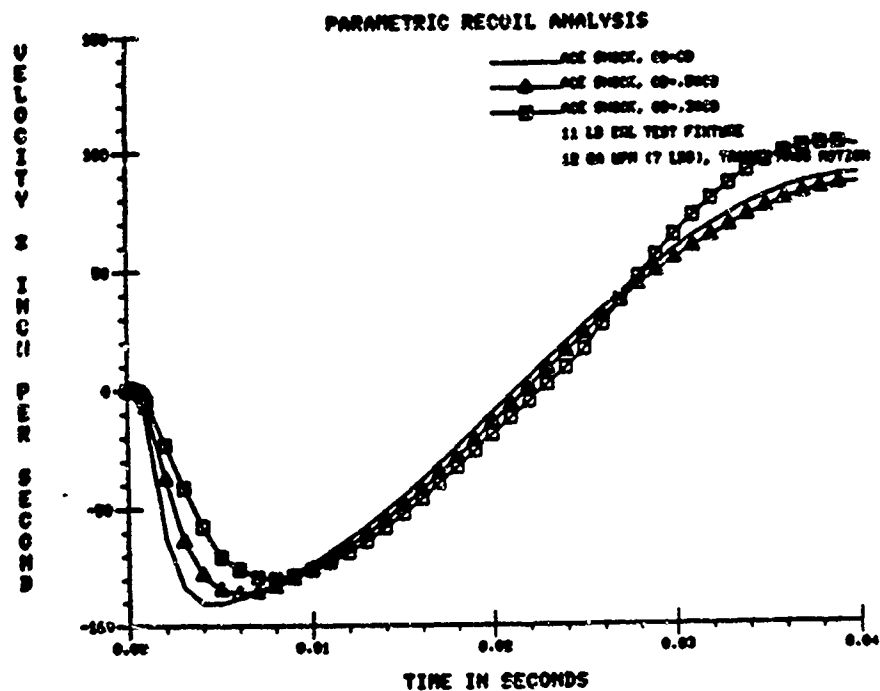


Figure 20. Velocity versus time for shoulder mass

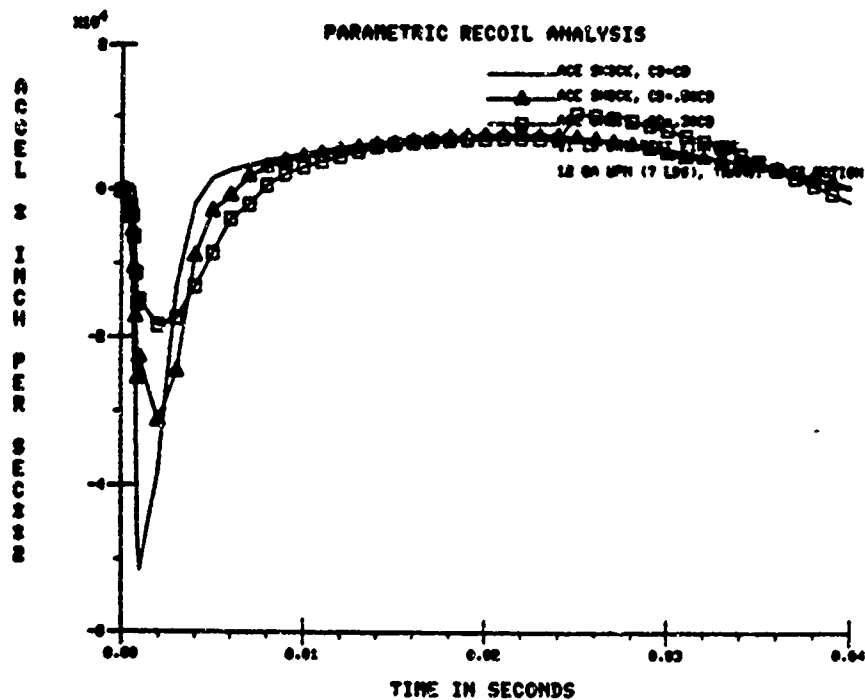


Figure 21. Acceleration versus time for shoulder mass

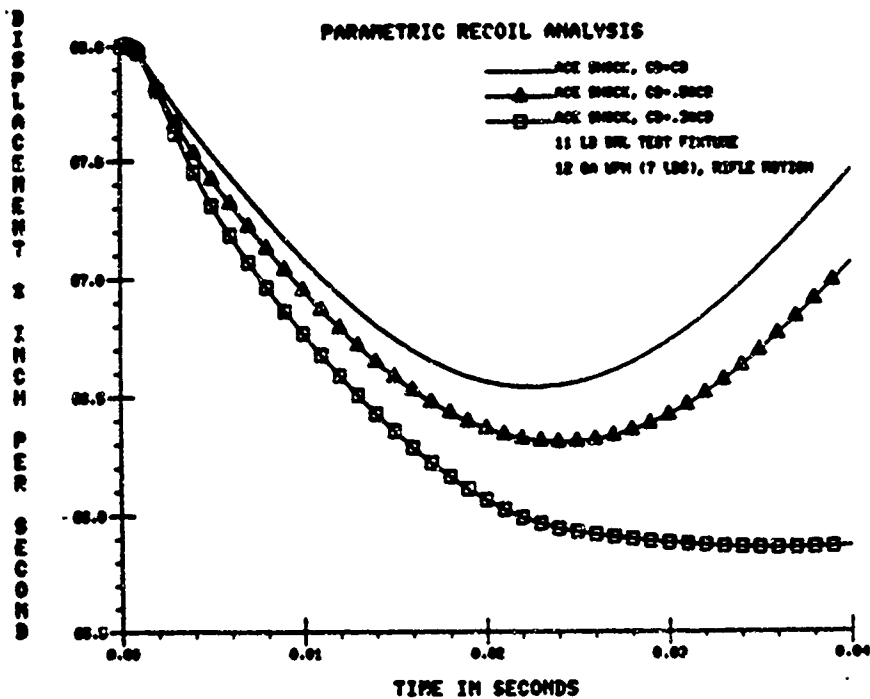


Figure 22. Displacement versus time for rifle

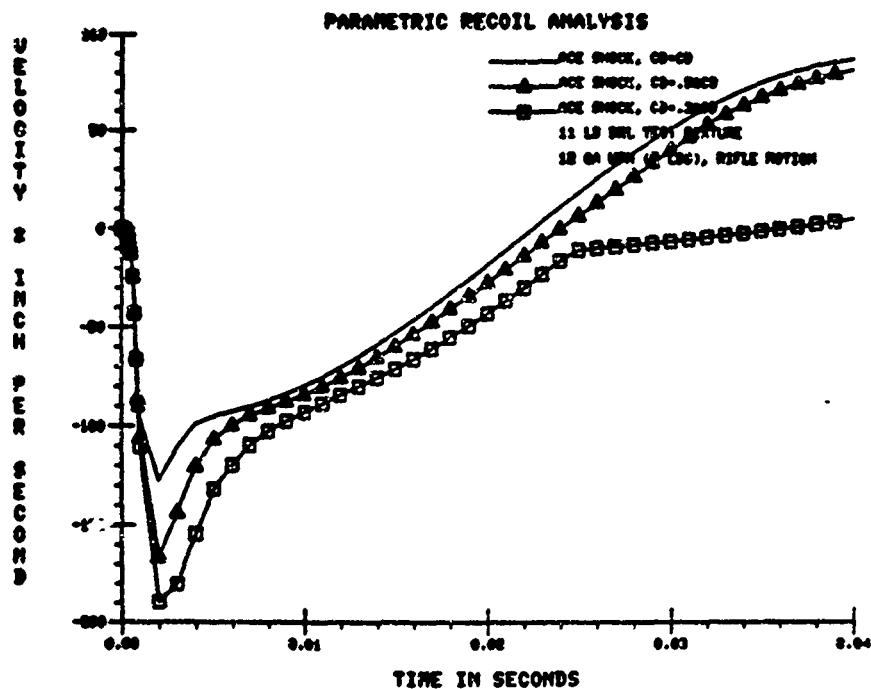


Figure 23. Velocity versus time for rifle

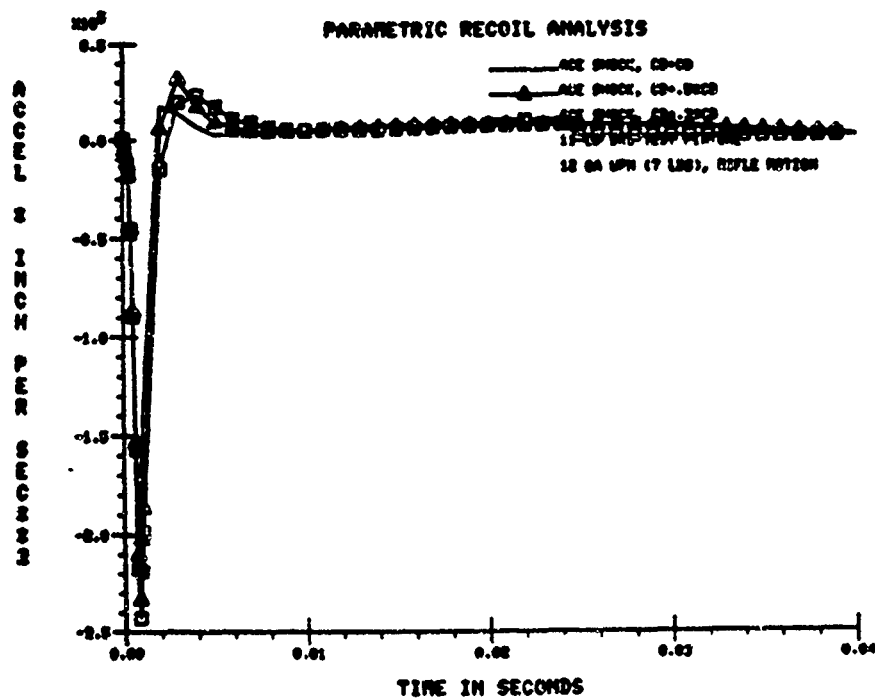


Figure 24. Acceleration versus time for rifle

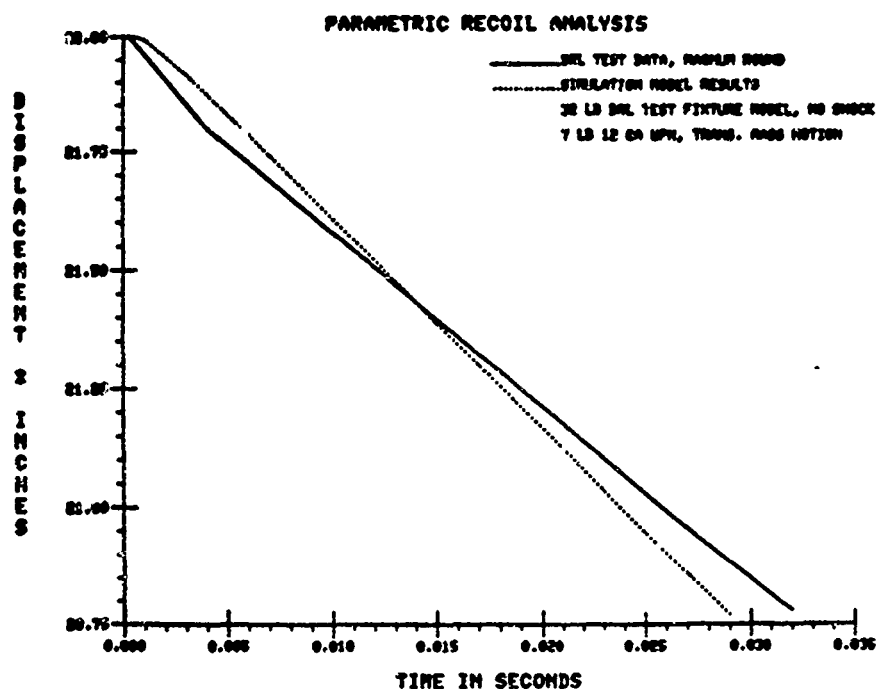


Figure 25. Displacement versus time for shoulder mass

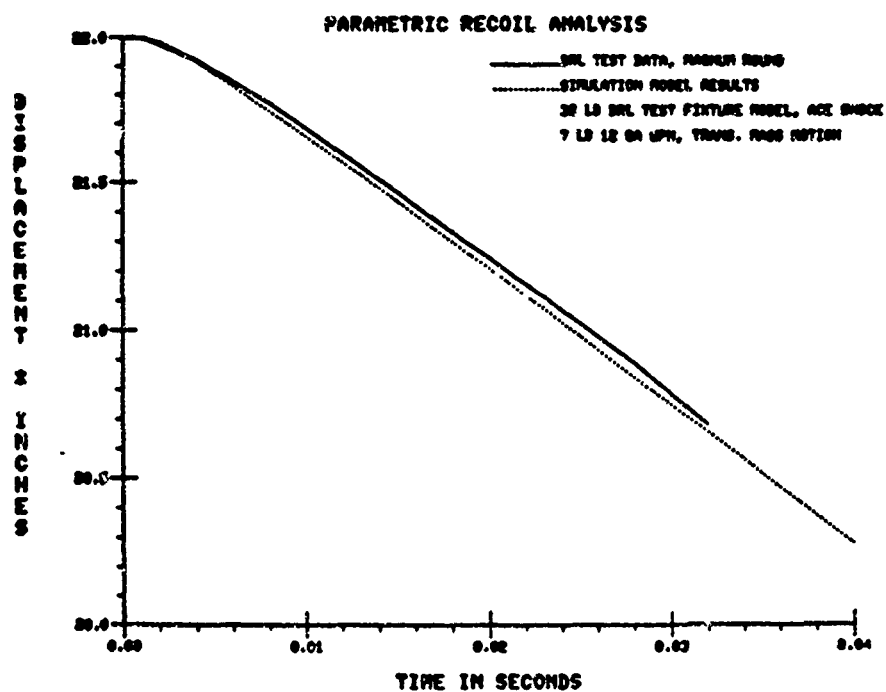


Figure 26. Displacement versus time for shoulder mass

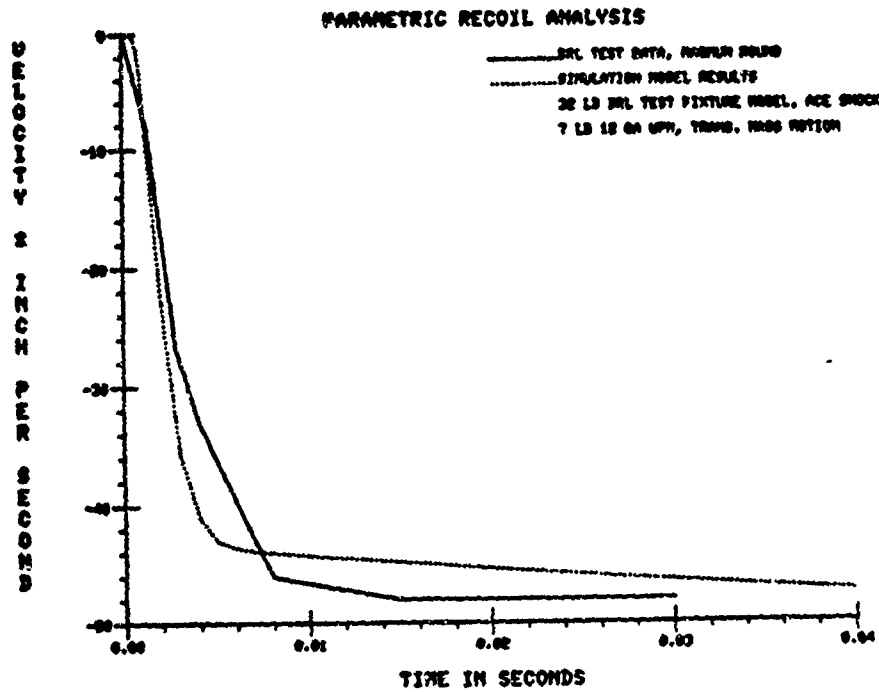


Figure 27. Velocity versus time for shoulder mass

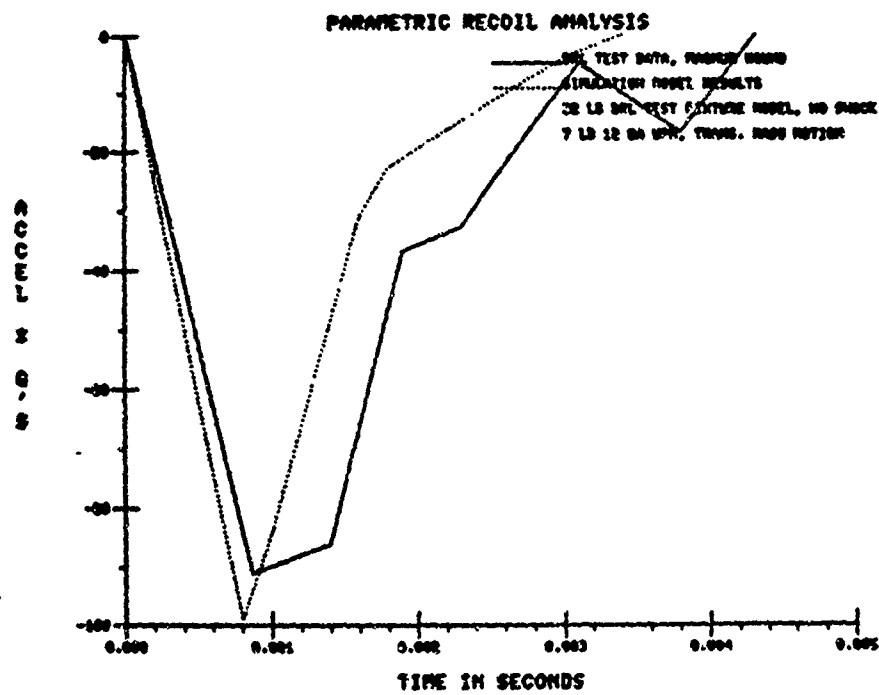


Figure 28. Acceleration versus time for shoulder mass

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